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Experimental study of the water depth effect and the impact of condensers connection in a new desalination system by HDH process, using solar energy

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Abstract

This work is part of increasing the profitability of a system of sea water desalination, single stage, held at the laboratory scale, using the method of Humidification Dehumidification (HDH) handset, instantaneous (shorten up the HDH cycle). This is essentially an experimental approach which consists on studying a new combination of HDH system based on the use of a plate condenser cooled by sea water and the envelope of the system cooled by the ambient air, subsequently, we test the effect of changing the water depth and the impact of condenser connection on the quantity of distilled water. The temperature of the free evaporation surface was also analyzed to determine its effect on the flow rate values of the distillate. This is a closed air system using solar energy and the cooling energy provided by the low temperature of sea water and ambient air. The results justify the feasibility of the proposed system, since we got encouraging results and quite comparable to other desalination systems using solar energy, those results also allow us to understand and predict the characteristics required for a new prototype of this desalination system.

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1. Introduction

For poor people, the opportunity of getting enough clean water to drink is decreasing each day (ex in Djibouti every citizen has a 19 m³ of water yearly), while the needs of drinking water for rich people keeps increasing (to produce a 1.5l bottle of natural mineral water, the process consumes 300l of potable water). So, to face this problem, the world needs a permanent resource of clean energy in order that the operation of producing water does not conduct to pollute the environment. The solar distillation is a promising solution to produce freshwater from brackish.

The solar distillation is one of many processes that clean water which can use any source of heat, such as the solar heating that proposes a lower technical solution price. In this kind of processes, water changes its phase into steam, using the solar energy. By hosting this steam, the air becomes humid and warm. This phase is called humidification. Then, the second phase is the conversion from gas to liquid state (water) by drying the humid air, using a cold surface, this phase is called dehumidification. The obtained water is cleaned from all kind of salts and others impurities.

The solar distillation is an ancient process that didn't get enough attention, perhaps due to its low yield compared to other desalination methods. Despite that fact, this cheap technology that anyone can build is the most used technology in Africa and India [1].

The system simplicity is not enough to cover the solar distillation problems, such as, the low yield of distillate per surface unit resulting from the low and variable temperature difference (ΔT) between the two exchange surfaces (evaporation and condensation surfaces), and the low efficiency of the still [2]. To enhance the productivity of the solar still, a variety of parameters have been tested by many researches till now, the basin surface, the evaporation surface, the water depth and the temperatures in the evaporation and condensation surfaces are the principle parameters that are affecting the productivity of the solar still.

Researchers have proposed several methods to increase the water temperature, efficiency and yield of solar stills such as: adding plus heat through flat plate collector or concentrating type devices such as reflector or parabolic dish. Rai and Tiwari [3] experimentally studied the single basin solar still coupled with a flat plate solar collector under forced circulation mode, the productivity was increased by 24% compared to a passive solar still. In the opposite way, Ali A Badran et al. [4] performed the same test but through natural circulation, and the yield was increased by 52%. Hitesh N et P. K. Shah [5] choose to decrease the inner glass temperature, and they test the effect of varying the glass thickness on a single basin solar still, and they find the more the glass is thin the more distillate rate is important.

The absorbing materials were tested too, by Akash et al. [6], and Nijmeh et al. [7] to study their effect in a solar still, and thus enhance the productivity of water, using a single-basin solar still with double slopes. Khalifa et al. [8] conducted an experimental study on new designs of basin type solar stills, and examined the effect of certain modifications that included preheating of feed water by means of a solar heater and utilizing external and internal condensers for steam condensation as well as for feed water preheating.

The principle of humidification dehumidification is rather developed in its separate form, i.e. a humidification unit where evaporation occurs, is separated from the dehumidification unit where condensation takes place, there is such a system developed by Ben Bacha Maalej and Y. Ben Dhia [9]. The same principle is also developed for desalination using the technique of greenhouse where humidification & dehumidification is gradual, using an open-air circuit, in agricultural greenhouse [10]. In this study, the system used is a new development of a process that produces fresh water from the humidification and dehumidification combined, instantaneous (shorten up the HDH cycle), and using closed air circuit, where we test the effect of changing the water depth and the effect of condenser connection on the quantity of distilled water.

2. Design and fabrication of distillation unit

The distillation system consists of three main parts as shown in schematic diagram fig.1:

- A plastic envelope ensures the greenhouse effect, thus acting like a condensation surface. The plastic used is cheap and available. A wooden umbrella is shading the whole plastic envelope so that unit doesn't receive any direct solar radiation.

- Two rectangular condensers made from aluminum are fed by seawater; the global area is $0.1 \times 0.9 \text{ m}^2$ per each condenser, and covering a catchment surface of $0.01 \times 0.9 \text{ m}^2$.
- A rectangular basin made from aluminum with an area of $0.9 \times 0.4 \text{ m}^2$, where the water is evaporated using an exchanger heated by a flat plate solar collector.

The distillation unit is simple and made using a cheap material such as plastic film and galvanized aluminum, the unit is installed in the laboratory where the experiences were taking place.

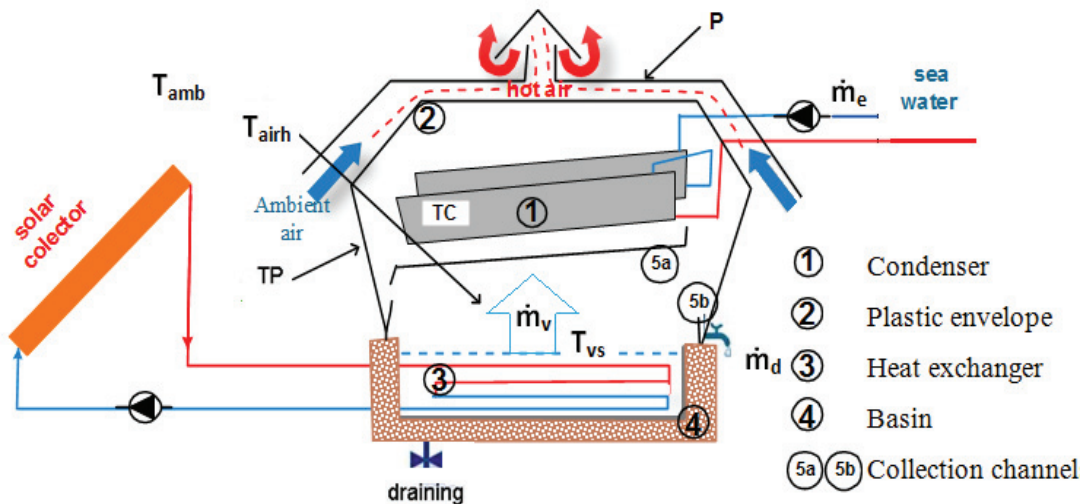


Fig.1: Schematic of the Solar System HDH single stage.

Nomenclature

T_{airh}	Temperature humidified air in the HDH system of a single floor.
TC1	Temperature of the condensation surface
TP2	Temperature of the transparent wall (on the surface of the wall)
T_{vs}	Water temperature in the evaporation surface
T_{amb}	Temperature of the ambient air
P	Plate solar shading
\dot{m}_d	the flow of distillate
\dot{m}_v	the flow of steam
\dot{m}_e	the flow of the sea water of cooling

3. Measurement instrument :

3.1. Temperature measurement :

The device is linked to an acquisition chain of HP7500-type to monitor temperature measurements provided by thermocouples type K.

3.2. Distillate rate measurement

The distillate collection is assured by a plastic pipe below the two condensers. The distillate obtained by the wall is collected using a fold with a slope made at the bottom of the cover wall so as to allow rapid evacuation of distillate. The measurement is carried out by a graduated cylinder with a pitch of 5 ml.

4. Experimental device & metrology installed

In laboratory scale experiments, different parameters are measured, mainly: the temperatures of the various parts of the system (wall, brine condenser, the internal air, etc...), and daily production. The results obtained have allowed us to see the feasibility of the equipment taking into account the daily production, in function of several parameters which are temperatures at the evaporation surface, humidified air, condenser, and the environmental air in order to conclude on the effectiveness of this system, and the improvements needed, we have also tested on the second place the effect of changing the water depth and the impact of condenser's connection on the rate of distilled water, to understand more the behavior of the system.

This method as illustrated in fig.1, consists of a basin (4) linked to an electric heater exchanger (3), the walls of the envelope consist of a plastic film (2) used to create a closed system in the shade, the entire walls surfaces are inclined in such way to ease the flow of condensed water droplets made over the walls, the system contains a condenser (1) designed especially for the condensation, these exchangers consist of two aluminum plates in an open circuit which circulates tap water to simulate the temperature of the sea water. The resistor heats the water mass contained in the basin at moderate temperatures to facilitate evaporation of water at the surface layer. By means of natural convection, water steam rises and reaches the level of the condensers and the envelope of the system where temperature is relatively lower compared to the one of the dew point of the humid air. The condensed water droplets slide and accumulate on the inner inclined surface of walls, and collect in collection channels (5a,5b).

5. Theoretical calculation of flow distillate:

The equations have been used in an experimental temperature range of [283K; 323K] ([10°C; 50°C]).

The estimation of the saturation pressure (P_{sat}) at the temperature of dry bulb is given by linear relation [11] depending on the temperature (T in °K) as follows:

$$P_{sat} = 0,14862 T - 0,36526.10^{-2} T^2 - 0,11242.10^{-3} T^3 \quad (1)$$

The estimate of the latent heat of evaporation (h_{fg}) as the following equation [12]:

$$h_{fg} = 3,1615.10^6 - 2,40714.10^3 T_{airh} \quad (2)$$

The expression of heat transfer coefficient by convection (between the water film & the surfaces of condensation) h_{cv} [13] is as follows.

$$h_{cv} = 0.884[(T_{vs} - T_c) + \frac{(P_{vs} - P_c)(T_{vs} + 273.15)}{268.10^3 - P_{vs}}]^{1/3} \quad (3)$$

The expression of heat transfer coefficient by evaporation-condensation h_{evap} between the water film and the surfaces of the condensation is [14]:

$$h_{evap} = 16.273.10^3 h_{cv} \frac{P_{vs} - P_c}{T_{vs} - T_c} \quad (4)$$

While calculating Condensate is possible by this equation:

$$\dot{m}_d = h_{evap} \frac{T_{vs} - T_c}{h_{fg}} \quad (5)$$

6. Results and interpretation

In laboratory scale experiments (equilibrium temperature T_{labo}), different parameters are measured, primarily the temperature of the evaporation surface of salt water, the temperature of the humidified air (humidity temperature and dew point temperature), the temperature of the condensing surfaces, and the daily production.

Measurements are taken each 30 minutes during 6.5h after starting the manipulation. Water is heated to 319K (46°C) and the water temperature is 289K (16°C).

The experiment allowed us to have several results that are presented in the below graphics.

6.1. The effect of water depth in the distillate rate:

Equilibrium temperature in laboratory is $T_{labo} = 286K$ ($T_{labo} = 13^\circ C$)

Fig.2 shows that as the water temperature increases, the temperature of the system parts increases in the same way, except for the condenser temperature (TC1), which keeps a cool surface compared to the high temperature of the basin water. One can note that with the decrease of the depth, the heating becomes faster, thus the transitional phase of heating is shortened. A disturbance may be noticed due to the heating cycle of the electrical resistance and the regulation from a test to another.

Fig.3 illustrates that the flow rate obtained by the condenser is higher than the one coming from the wall, if we compare the surfaces -condenser ($0.2 * 0.9 m^2$); walls ($3 * 0.8 m^2$)-. This is explained by the temperatures of the two surfaces (the temperature of the condensers does not exceed $19^\circ C$ against the temperature of the walls of the order of $26^\circ C$) and also due to the location of each surface (condenser is perpendicular and close to steam, walls are parallel and remote to flow). It is also noted that the delay is incrementing with increasing of water depth, the same way as the one observed for the temperatures, for example 700 ml value is reached at time 210 minutes in a depth 12 mm, 270 minutes in a depth of 20 mm, and 330 minutes for a depth 28 mm. The daily flow rate is 1350ml for 12mm, 1150ml for 20mm, and 1070 ml for 28mm.

In the three manipulations (Fig.4: a, b, c), the theoretical flow rate is very close to the actual flow created by the wall and the condenser. The variation in the depth does not affect the participation of the two surfaces in the total flow: the wall produces 55% of the total condensate in the 3 cases as shown in Fig.4d.

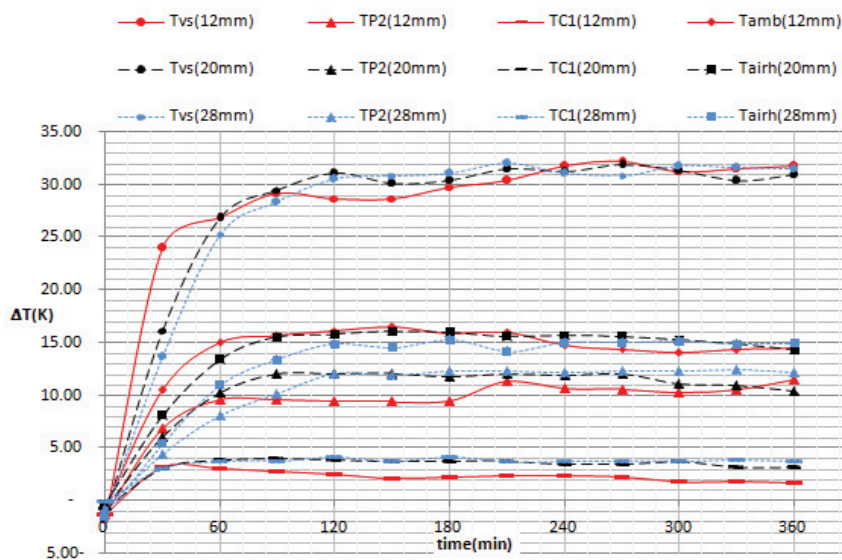
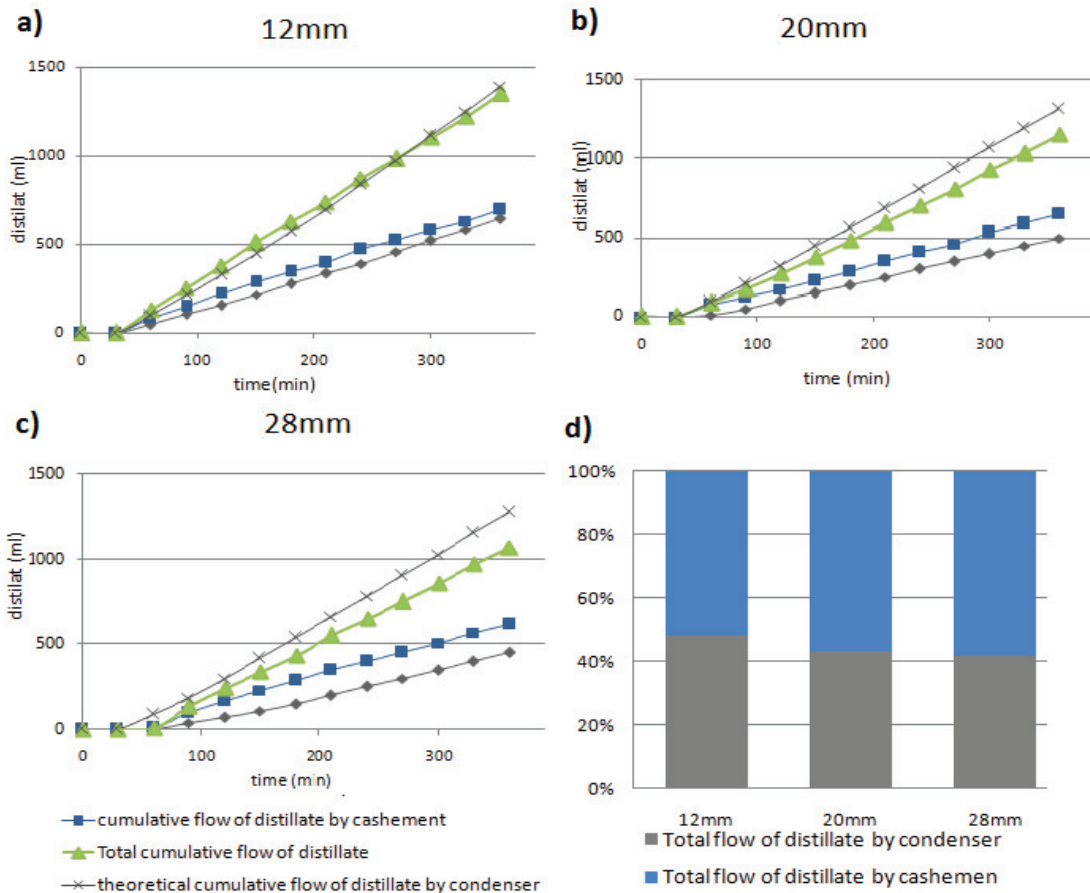
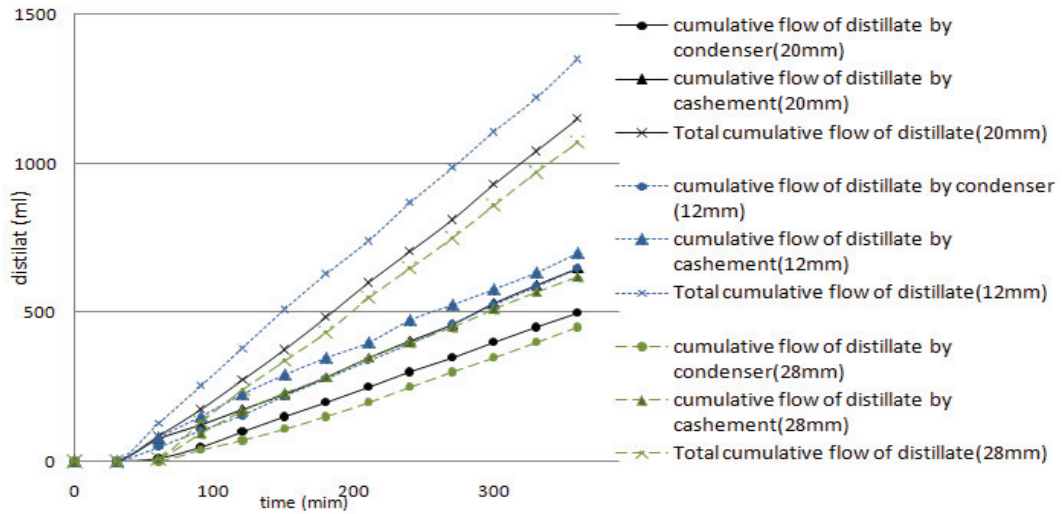


Fig. 2: Evolution of temperature difference between the ambient and the different parts of the system by each depth (12mm;20mm;28mm).



6.2. The system behavior with one condenser, two condensers branched in series and in parallel

Taking into a count the first experiment, we chose to do the next experiment with a depth of 12 mm. Equilibrium temperature in laboratory is $T_{\text{labo}}=288\text{K}$ ($T_{\text{labo}}=16^{\circ}\text{C}$).

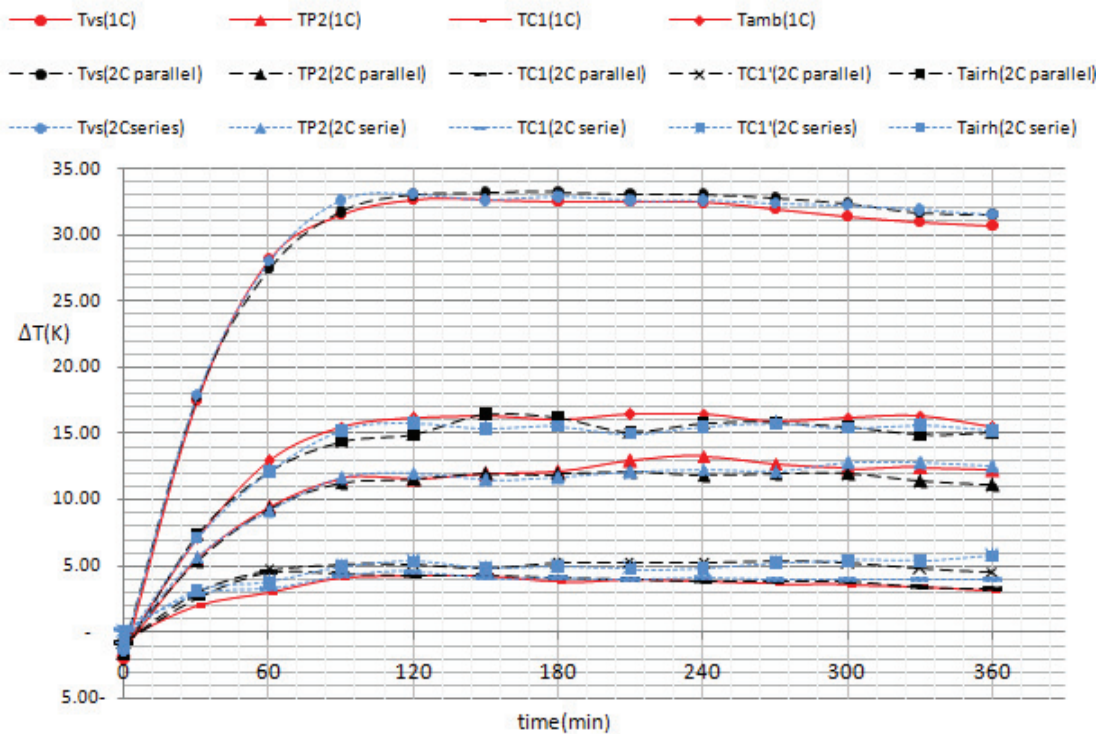


Fig.5: Evolution of temperature difference between the ambient and the different parts of the system by arrangement.

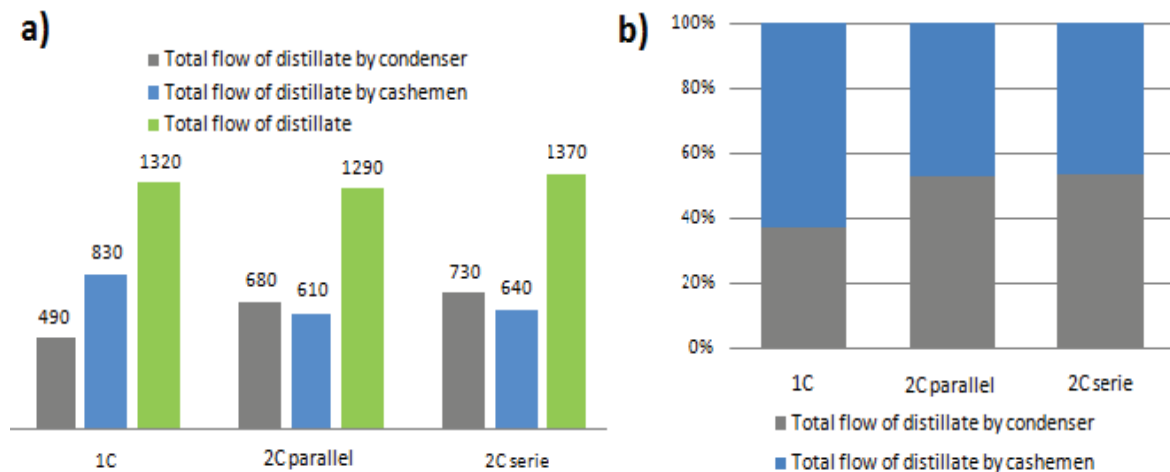


Fig.6:a) Total distillate produced by surface and by each connection in mm; b) Participation of walls and condenser; in percentage of the total distillate flow rate

Fig.5 shows that the temperatures are the same and having the same evolution in the three cases, in each part of the system.

Fig.6a shows that the total flow rate of distilled water is the same in the three connections. In the case of one condenser connection the flow rate is 30% lower than the two connections. In the fig.6b the participation of the walls using two condensers in parallel or series connection is the same 47%, but with the use of one condenser the walls give rate of 63%. One notices that the walls take the remaining steam that the much colder surfaces can't catch.

7. Conclusion

Distillation is a phenomenon depending on several parameters, among others: Design, connection of condenser and water depth, those parameters cited are the subject of this work.

This research allowed us to justify the feasibility of the proposed system since we got encouraging results and quite comparable to the desalination systems using solar energy in order to produce desalinated water as distillers solar with poor energy consumption for pumping seawater.

The study also defended the use of the walls of the envelope system as collection surface, in addition to the condenser cooled by the sea water, and the use of minimum depth of water to get a quick responding from the system instate of adding mass that increases the inertia of the system.

The study shows that adding the condensers will not increase the productivity of the system, if the evaporation surface stays the same. but improving the evaporation surface(using as example augmentation of water temperature) in a desalination unit of 1 m² evaporation surface, that has 10 condensers, each one occupies 0.09 m² can gives about 7l/day of fresh water, adding almost 50% of wall's condensation. The unit could give 11.5l/day without taking in count the wind energy. Therefore, the use of such desalination unit in small or big scale will be very attractive to supply remote poor areas in Morocco with fresh water for domestic uses since the electrical energy requirement is significantly low.

To achieve a greater efficiency of our system we work on a new surface of the walls component system coverage and condensation exchanger, at the end, the transition stage of experimental and theoretical studies of various parameters on the field is required in the second phase to consolidate the results obtained.

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